The role of the high resolution weather forecast in estimating the run-off using a simple hydrological model

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Abstract
Recent and repeated episodes of severe weather in Italy have stressed the need to have a sufficiently accurate forecast to give adequate warning to the involved areas. The impact of the precipitation, however, is also a function of the characteristics of the hydrological basin. From this point of view, a rather startling example is the disaster which hit the Campania region on 5th May, 1998 in which a moderate precipitation (about 100 mm in 24 h) produced a huge landslide which killed or injured several tens of people and produced serious damage to the area. Such localized events require among other things the use of a high resolution weather forecast. In this paper, a forecast of the Campania event using a limited area model at 3 km grid resolution is presented. The forecast rainfall at several grid resolution is used to initialize a simple hydrological model to estimate the run-off. The numerical experiments suggest that high resolution may be a key factor in predicting the run-off.

Key words *high resolution forecast – heavy precipitation*

1. Introduction

The precipitation forecast over complex topography is still a challenging problem. The Mediteranean area is often affected by catastrophic events related to heavy precipitation. In the last 10 years more than one flood hit Italy producing severe damage.

During 2-5 May 1998, cyclogenegesis over the Tyrrhenian sea produced rainfall over Campania, a region of Central Italy (fig. 1); the rainfall caused a severe landslide destroying several villages and killing many people.

To prevent these events, both a good forecast of the precipitation and knowledge of the characteristics of the terrain are necessary. Most of the Italian weather forecasts are made using hydrostatic models reaching resolutions lower than 9 km. A few studies using this resolution for the model simulation showed good skill for the precipitation forecast but at times missing the location of maximum rainfall (Paccagnella *et al.*, 1992, 1995). The hydrostatic version of the MM5, from Penn State/National Center for Atmospheric Research (PSU/NCAR), also showed good skill for the precipitation forecast, but the location of the maxima of the rainfall were not correct (Ferretti *et al.*, 2000b), whereas the same event analyzed using the non-hydrostatic version of the MM5 showed better results (Paolucci *et al.*, 1997). A study of the Piedmont flood using the non-hydrostatic version of the MM5 showed good skill for both the precipitation amount and the extent of the rainfall (Ferretti *et al.*, 2000a). On the other hand, a comparison between the MM5 score and a few other models (Richard,

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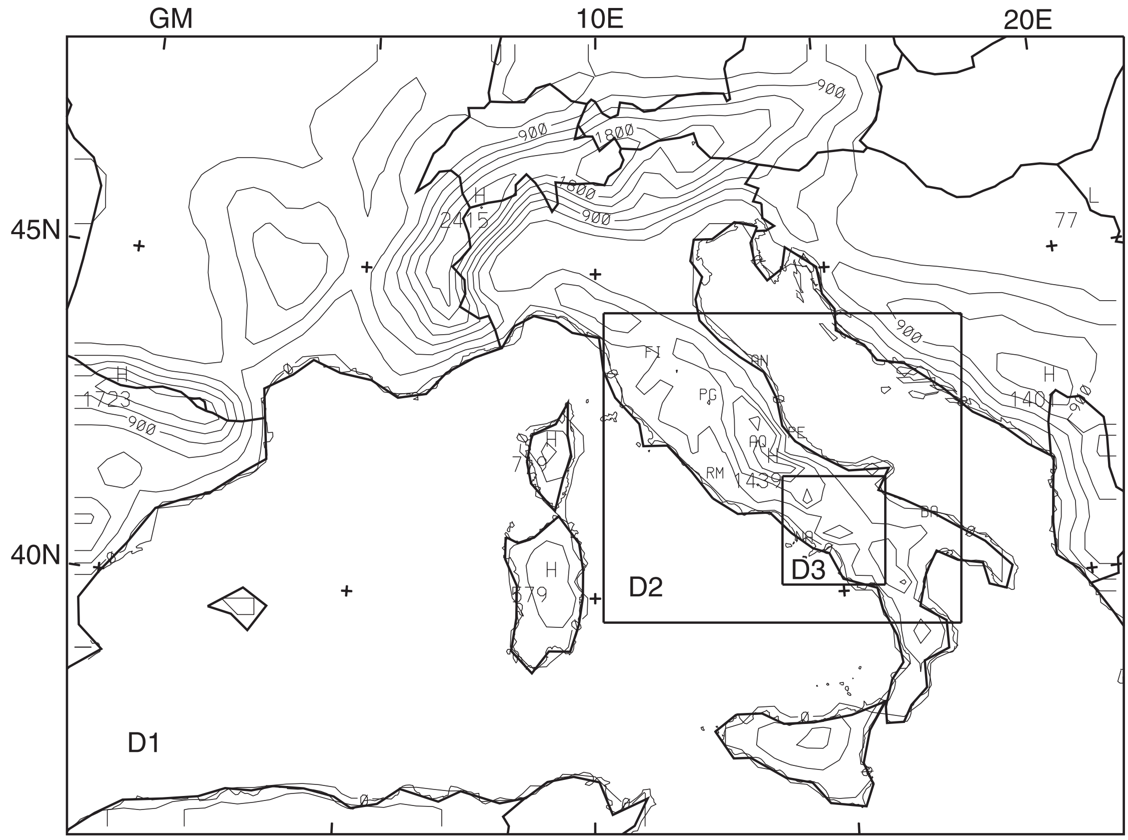


Fig. 1. Model domains: domain 1 has grid resolution of 27 km, domain 2 of 9 km and domain 3 of 3 km.

1998) revealed a poor skill by the MM5, but the resolution used for that study was 10 km.

Recently, in the framework of cooperation between University of L'Aquila and Scientific and Technology Park of Abruzzo the MM5 has been made operational, being the only high resolution non-hydrostatic model used for weather forecast in Italy. The probability of occurrence of post events (landslides and avalanches), like the one analyzed in this study, is known to be correlated with complex statistical moments of the meteorological variables (in this case precipitation) besides, of course, the structural parameter, like ground conditions. Therefore, a high resolution forecast of the meteorological variables may help to forecast these events.

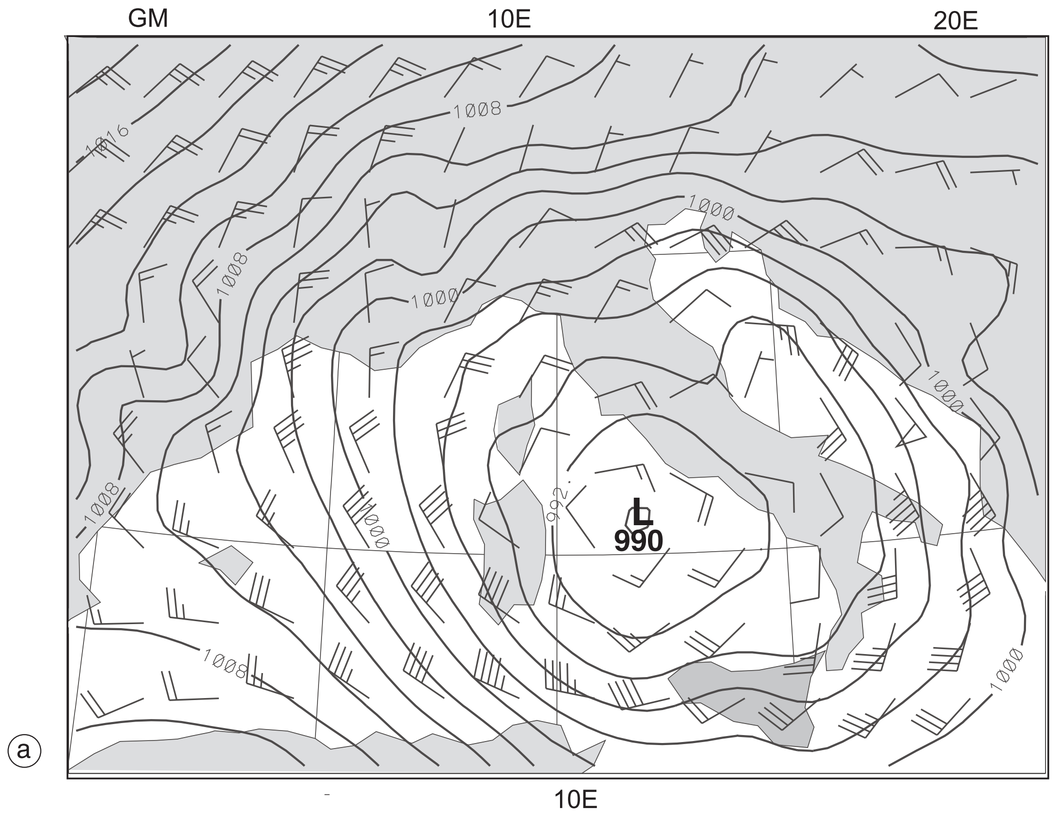
An attempt to forecast the hydrological impact of this event is presented: the run-off, related to the heavy precipitation of this case, using an off line scheme for the soil is computed.

The aim of this paper is to show how a high resolution weather forecast may help to correctly forecast a few hydrological parameters. For this purpose, sensitivity tests to the grid resolution are carried out using a non-hydrostatic model. The model results are used to initialize a simple hydrological scheme, the Biosphere-Atmosphere Transfer Scheme (BATS).

The meteorological characteristics of this event and the precipitation recorded by a high resolution rain gauge are presented in Section 2; the experimental set up for both MM5 and BATS is discussed in Section 3. The results are presented in Section 4 and the conclusions are given in Section 5.

2. Meteorological characteristics

This event was characterized by cyclogenesis over the Mediterranean Sea a deep low level depression entering this region from the south intensified over the Tyrrhenian Sea on 3rd May, and reached a minimum of 990 hPa by 4th



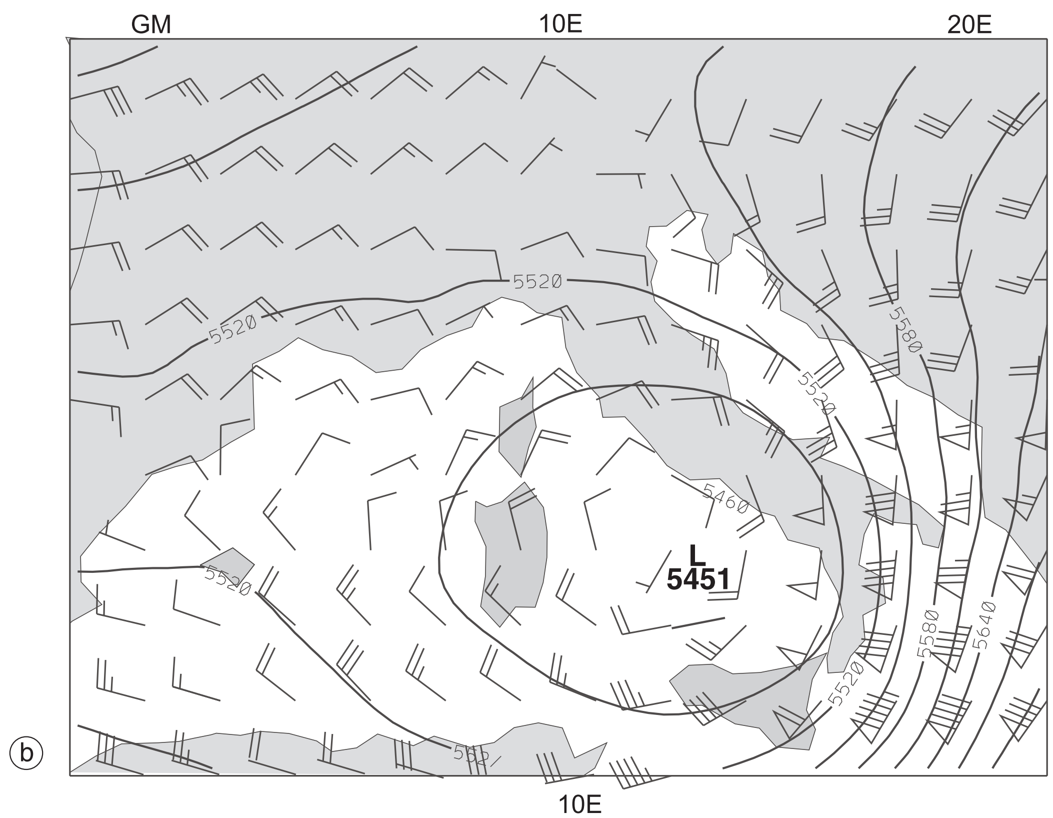


Fig. 2a,b. Ecmwf data analyses for 4th May at 0000UTC: a) sea level pressure (c.i. = 2 hPa) and wind (one barb = 10 knots) at 925 hPa; b) 500 hPa-height field (c.i. = 30 m) and wind (one barb = 10 knots).

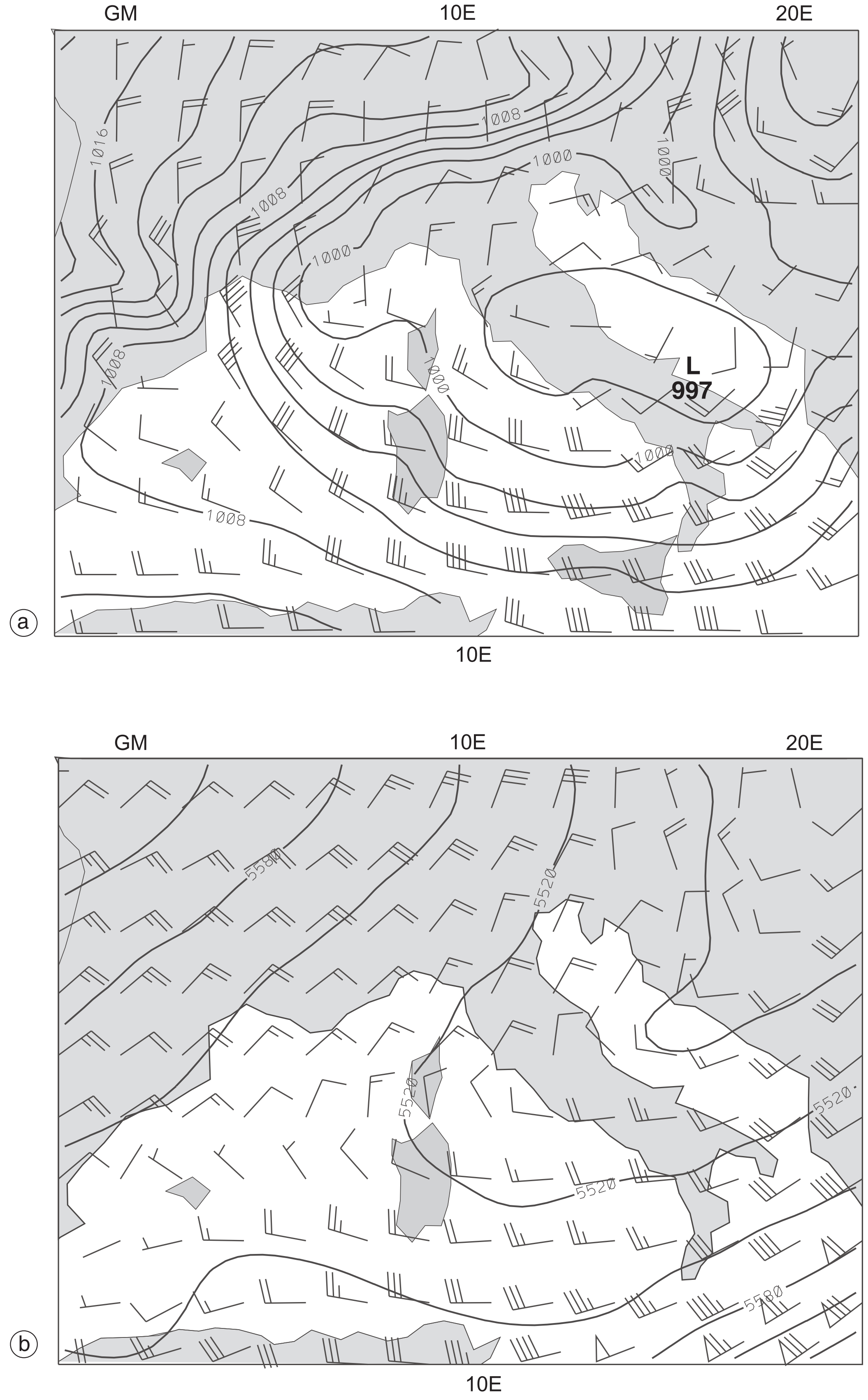


Fig. 3a,b. As fig. 2a,b but for 4th May at 1800UTC.

May at 0000 UTC (fig. 2a). The cyclone was associated with a cut-off low (fig. 2b) which swept over the Mediterranean area. During its passage, the axis rotated clockwise producing a westerly flow both at upper and lower levels by the late afternoon (fig. 3a,b). Advection of warm and humid air persisted for the rest of the day over most of Southern Italy. The day before the event, the local rain gauge recorded light precipitation over the disaster area, reaching about 75 mm in 24 h (not shown). During 5th May the rainfall intensified both over this area and south of it (fig. 6, the rain gauge data are superimposed to the model results). However, the amount of rain was less than half of that recorded during the Piedmont flood of 1994, which was a major severe weather event. Therefore, it makes sense to assume that the damage produced by precipitation is strongly related to the nature and morphology of the terrain for this event, besides the correlation with the meteorological variables as already pointed out.

3. Numerical experiment set up

3.1. *Mesoscale model description*

The MM5 (PSU/NCAR) is a non-hydrostatic limited area model fully compressible at the primitive equations (Dudhia, 1993; Grell *et al.*, 1994). To enhance to forecast over the area of the slide, three domains two-way nested and 24 vertical levels (sigma coordinate) unequally spaced are used. The MRF (Troen and Marth, 1986; Hong and Pan, 1996) Planetary Boundary Layer parameterization and the Grell (Grell, 1993) cumulus convection parameterization associated with an explicit computation of rain water for domains 1 and 2, whereas only the last one for domain 3, are used. The forecast is made using three domains, the first domain (1) has a resolution of 27 km and contains 50 (latitude) $\times$ 66 (longitude) grid points; the intermediate domain (2) has 9 km resolution and 58 $\times$ 67 points and the high resolution domain (3) has 61 $\times$ 58 grid points with a 3 km grid size. To enhance the local forcing by the soil a 1 km resolution land use data (USGS) specifies the vegetation and the soil characteristics.

Table I. The model simulation performed using different nested levels. D11 for model simulation using one domain only. D21,2 for model simulation using two domains. D31,2,3 for model simulation using three domains.

Model	Domains	Grid size (km)	Acronimus
MM5	1	27	D11
MM5	2	27 9	D21 D22
MM5	3	27 9 3	D31 D32 D33

A few model simulations are made to verify the sensitivity of the run-off to the grid resolution of the MM5. A simulation using only one domain (D11) at 27 km is performed, and the results are compare with both the observations (OBS) and the results of domain 1 (D21) obtained by using two domains two way nested at 27 km and 9 km respectively for domains 1 and 2. A last simulation performed using three domains (D3) respectively at 27, 9 and 3 km for domains 1, 2 and 3 is performed. The D3 results are compared with both the observations and the previous simulations: domain 2 of two domains only (D22) is compared with domain 2 of three domains (D32), and finally D33 (domain 3) is compared with the OBS only (table I).

All the MM5 forecasts are initialized by using the European Center for Medium-Range Weather Forecast (ECMWF) data analysis and the boundary conditions are upgraded every 6 h by using ECMWF forecast.

3.2. *Hydrological model description*

The MM5 output is coupled off line with the Biosphere Atmosphere Transfer Scheme (BATS) to evaluate the run-off expected from the precipitation. BATS can predict a number of soil variables based on the specification of soil characteristic and vegetation cover.

The BATS (Dickinson *et al.*, 1986) estimates the transfer of momentum, heat and moisture between the surface and the atmosphere when the boundary meteorological conditions are specified, it also computes soil moisture content and run-off. In the past, this scheme has been coupled to the MM4, the hydrostatic version of the MM5, by Giorgi (1989) for climate studies. BATS is applied to the landslide area and it is initialized by using both the observations and the MM5 precipitation, temperature and wind forecast for 5th May. The 1 km land-use for the MM5 allow for estimating the vegetation type in the slide area: cropland and woodland mosaic with urban and built-up land in the nearby area is mostly the soil type of this region.

4. Results

4.1. *MM5 precipitation forecast*

Two operational forecasts covering the whole period were made: one starting at 1200UTC on 3rd May and lasting for 48 h; the second one starting at 1200UTC on 4th May and ending at 1200UTC on 6th May. The results of both of them, for the experiments in table I, are used for initializing the BATS. For each run the first 12 h are discarded in order to take into account the spin up time, therefore, the two forecasts have an overlapping period from 0000UTC of the 5th to 1200UTC of the same day. The OBS are available from 0000UTC of the 4th to 0000UTC of the 6th. The comparison between the model rainfall and the observations is now presented.

To ensure a multi-scale analysis all the results of the model on domain 1, at the same resolution but using different nesting levels, are compared with the OBS. The same comparison is performed for domain 2.

The comparison between the 24 h accumulated precipitation for D11 (fig. 4a) and the OBS (fig. 6) shows a large underestimation of the rainfall, furthermore the location of the maximum is too far inland. If higher resolution associated with the two way nesting for domains 1 and 2 (D22) is used, a measurable improvement both in the total amount of rain and in the position of the maximum is found (fig. 4b). Indeed, the most intense precipitation has now moved toward the coast. Sarno, the town most affected by the flood,

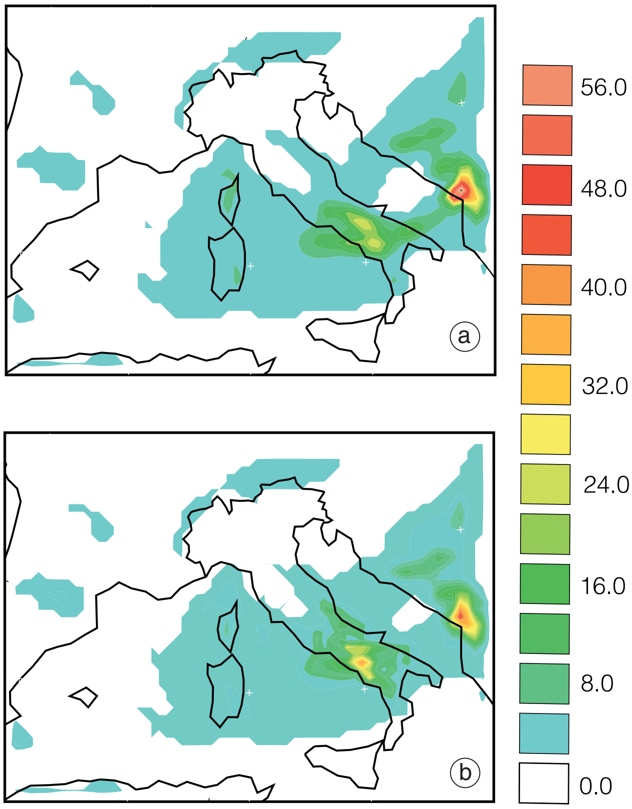


Fig. 4a,b. 24 h accumulated precipitation (mm) at ending at 0000UTC 5th May predicted on domain 1 by using: a) one domain at 27 km grid resolution; b) 2 domains two-way nested at 27 and 9 km resolution respectively.

is located in this area. The differences between D11 and D21 are produced by the feedback process due to the two-way nesting technique; indeed, in this case a feedback from the fine mesh to the coarse resolution ensure the small-scale forcing to affect the large scale. The rainfall produced on domain 2 (D22, fig. 5a), which feeds back to domain 1, is closer to the OBS (fig. 6) than both D11 and D21. This imply a large gain in the precipitation forecast by increasing the resolution only. If three domains two way nested are used, the rainfall on domain 2 (D32) is further improved (fig. 5b). It can be easily noted that there is a considerable improvement in the rain predicted in both cases D22 and D32 with respect to domain 1.

A direct comparison between the high resolution rainfall (D33) and the OBS is now presented. Figure 6, where the rain gauges data

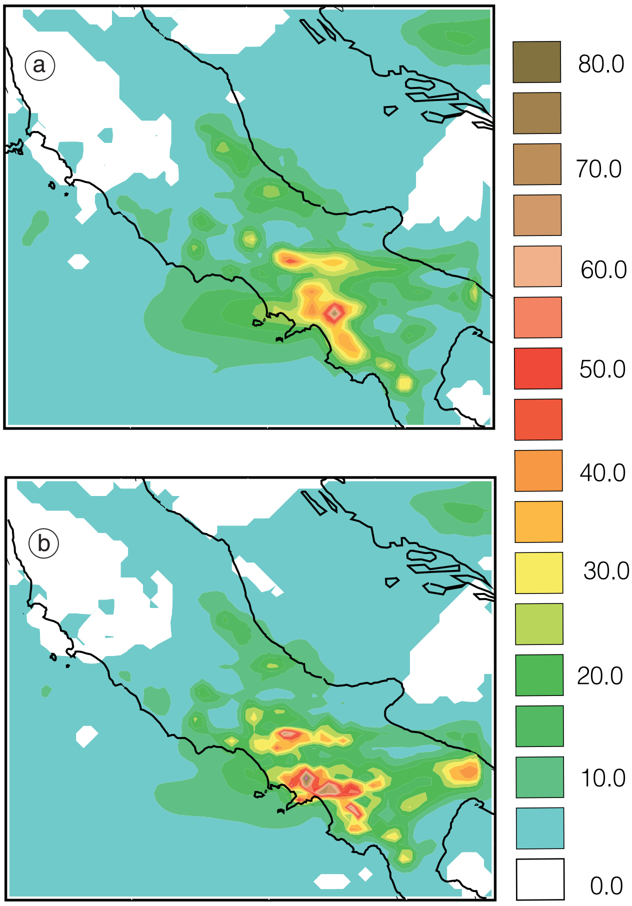


Fig. 5a,b. As for fig. 4a,b but on domain 2 using a two way nesting: a) between domain 1 and 2 at the same resolution of fig. 4b; b) between domain 2 and 3 at 9 and 3 km resolution, respectively.

are superimposed to the model prediction, shows that the rainfall in the southern area agrees reasonably well with the D33 results, with peak values around 100 mm in 24 h. On the other hand, the model seems to underpredict the rain in the southernmost region while the northern patch of rain seems an almost complete artifact. The rain produced by the model is strongly influenced by the updraft forced by the orography and this may very well be the cause of the northern patch of rain.

The 24 h accumulated precipitation recorded (not shown) light precipitation starting from 1st May and decreasing by the end of 3rd May; during 4th May a maximum of the rainfall reaching 84.6 mm in the Campania region was recorded, whereas during the day of the slide 103 mm are reached south of the slide area. In the disaster area only 60 mm are reached. D33 shows a similar pattern to the OBS, both for the amount and the distribution of the precipitation, reaching values higher than 50 mm. The day before the catastrophe light precipitation occurred reaching 24.4 mm and doubling during the following 24 h. During the first day, the precipitation forecast (not shown) produced 25 mm, and it reached 50 mm the day after (fig. 6), showing a correct tendency. These results confirm the good skill of the model in forecasting precipitation even at very high resolution. Indeed, the model forecast shows a very good agreement with the high resolution precipitation data on the fine mesh; the precipitations are highly localized, and the maximum of the precipitation is close to the hill where the landslide occurred.

4.2. *Run-off results*

An attempt to estimate the run-off using BATS is now presented. The observed rainfall is used to estimate the run-off that will be used

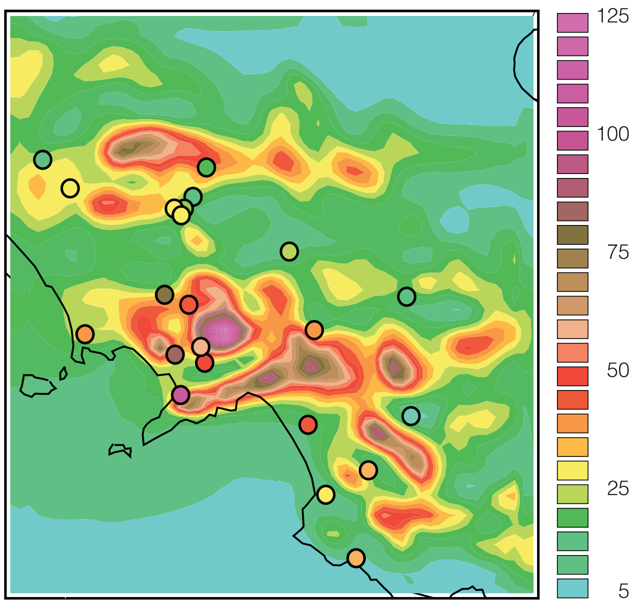


Fig. 6. 24 h accumulated precipitation (mm) ending at 0000UTC 5th May both predicted on domain 3 using three domains two way nested and observed at a few stations (colored circles). The circles are filled with the color corresponding to the scale shown on the right.

as reference (OBS). The run-off produced by BATS using the rainfall from D11, D22 and D33 is compared with OBS. To ensure a correct response by BATS to the precipitation event the simulation started a few day before the disaster to allow the soil to reach the right amount of soil moisture. In fact, the day before the disaster precipitation occurred making the soil wet. The run-off produced by this precipitation is shown on fig. 7a-d before 3rd May, but it is not real.

The comparison between the run-off produced by both the observed and the forecast rainfall shows (fig. 7a-d) that as the resolution increases the signal get closer to the real one. Indeed, the rainfall obtained using one domain only produces a strong underestimation of the run-off (fig. 7b), only a weak signal during May 5th is obtained. If the resolution is increased, that is the rainfall from D22 is used to estimate, the run-off (fig. 7c), a slight improvement is obtained. Finally, if higher resolution is used, the run-off (fig. 7d) is in good agreement with that obtained forcing BATS with the observations (fig. 7a). The maximum run-off is still underestimated but the bimodal structure is clearly reproduced by the high resolution rainfall. It is clear from these results that increasing the weather forecast resolution the right amount of run-off is obtained.

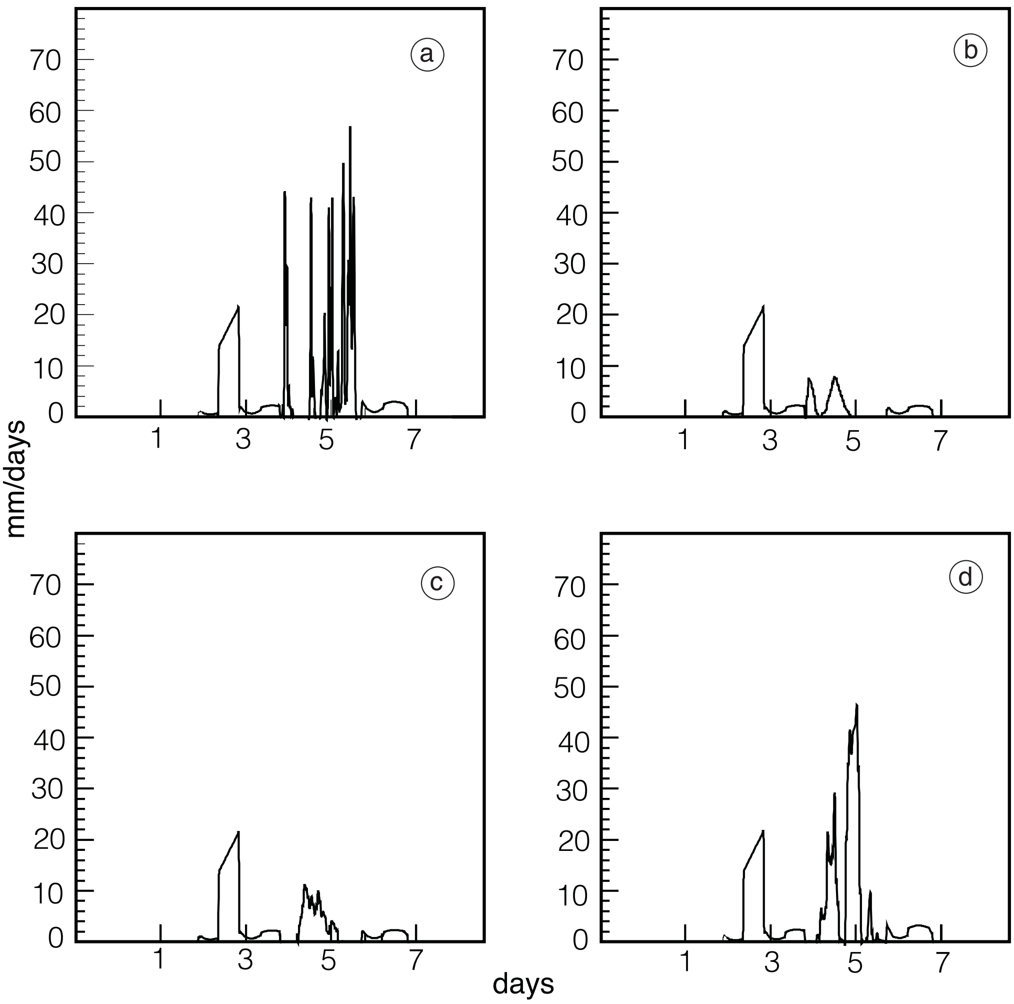


Fig. 7a-d. The run-off in mm/days from 1 to 7 May 1998, obtained when BATS is coupled to: a) the observations (OBS); b) the rainfall produced by the model simulation performed using one domain only at 27 km; c) the rainfall produced by the model simulation performed using 2 domains with the highest resolution being 9 km; d) the rainfall produced by the model simulation performed using three domains with the highest resolution being 3 km.

5. Conclusions

The MM5 forecasts and the run-off produced by BATS show that increasing the resolution a large improvement in both the rainfall and the run-off is obtained. At low resolution the rainfall is largely underestimated and the maximum of the precipitation is displaced. Increasing the resolution (up to 3 km), both a good precipitation forecast and an estimation of the run-off in very good agreement with the one produced using the observed precipitation are found. The high resolution rainfall forecast is in good agreement with the observations, but a model tendency to overestimate the rainfall, if strong uplifting is present as for the mountain regions, is found. However, D33 is the only one able to separate areas with different rainfall. These results suggest that the high resolution is required to correctly evaluate the hydrological impact. Indeed, even using a simple hydrological model the role of the grid resolution in the rainfall forecast is highlighted.

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